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AN EXPERIMENTAL FACILITY FOR OXIDATION AND BIAXIAL DEFORMATION STUDIES OF ZIRCALOY-4 FUEL CLADDING SAMPLES

Report No 86-342-K

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ABSTRACT

A test facility capable of oxidizing and simultaneously biaxially deforming Zircaloy-4 fuel cladding samples has been developed at Ontario Hydro Research Division. The development of this test facility was motivated by the need to generate materials data suitable for use in the analysis of a number of post-shutdown accident scenarios and fuel handling incidents in which the fuel at low decay power levels is postulated to heat up due to degraded cooling conditions. The test facility consists of: a) in-house designed and built tube furnaces for specimen heating under closed-loop control; b) an in-house designed and built pressurizing circuit for deformation under biaxial conditions; c) a microprocessor-based data logger for data acquisition; d) an elapsed time indicator for accurate monitoring of time to failure in testing under biaxial conditions. Examples of typical test facility component performance data presented indicate that a large variety of oxidation and elevated temperature biaxial tests may be carried out using the newly developed facility.

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84-533-450	823.22	February 16, 1987	86-342-K

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EXECUTIVE SUMMARY

AN EXPERIMENTAL FACILITY FOR OXIDATION AND BIAXIAL DEFORMATION STUDIES OF ZIRCALOY-4 FUEL CLADDING SAMPLES

E.T.C. Ho and A. Donner

Materials data on the oxidation and deformation behaviour of CANDU reactor Zircaloy-4 fuel cladding for temperatures in the range 673-1173 K are very limited. Unfortunately, such data are required in the analysis of a number of post-shutdown accident scenarios and fuel handling incidents in which the fuel at low decay power levels is postulated to heat-up due to degraded cooling conditions. To generate the necessary data, a test facility capable of oxidizing and simultaneously biaxially deforming Zircaloy-4 fuel cladding samples has been developed at Ontario Hydro Research Division.

The test facility consists of: a) in-house designed and built tube furnaces for specimen heating under closed-loop control; b) an in-house designed and built pressurizing circuit for deformation under biaxial conditions, c) a microprocessor-based data logger for data acquisition; d) an elapsed time indicator for accurate monitoring of time to failure in testing under biaxial conditions. Examples of typical test facility component performance data presented indicate that a large variety of oxidation and elevated temperature biaxial tests may be carried out using the newly developed test facility.

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TABLE OF CONTENTS

		PAGE
1.0	INTRODUCTION	1
2.0	MAJOR COMPONENTS OF THE FUEL CLADDING TEST FACILITY	1
2.1	The Heating System	1
2.2	The Pressurizing System	2
2.3	The Data Acquisition System	2
3.0	PERFORMANCE CHARACTERISTICS OF THE TEST FACILITY	3
3.1	The Heating System	3
3.2	The Pressurizing System	3
3.3	Examples of Test Results Obtainable	3
4.0	SUMMARY	4
	ACKNOWLEDGEMENTS	4
	REFERENCES	5
	FIGURES	6
	DISTRIBUTION	last page

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TO: Dr. D. Mills
Director of Research

AN EXPERIMENTAL FACILITY FOR OXIDATION AND BIAXIAL DEFORMATION STUDIES OF ZIRCALOY-4 FUEL CLADDING SAMPLES

1.0 INTRODUCTION

Materials data on the oxidation and deformation characteristics of CANDU reactor Zircaloy-4 fuel cladding for temperatures in the range 673-1173 K are very limited. Unfortunately, such data are needed/1/ in the analysis of a number of post-shutdown accident scenarios and fuel handling incidents in which the fuel at low decay power levels is postulated to heat-up due to degraded cooling conditions. In view of this, a test program was proposed/2/ to generate the required materials data. The test program was subsequently approved and funded by the Fuels and Physics Department of the Technical and Training Services Division. As described in the proposal, the generation of suitable test data required the development of a test facility at Ontario Hydro Research Division which can oxidize and simultaneously biaxially deform Zircaloy-4 fuel cladding samples. The following describes the test facility designed, developed and built by Materials Integrity Section personnel.

2.0 MAJOR COMPONENTS OF THE FUEL CLADDING TEST FACILITY

The test facility developed for testing of Zircaloy-4 fuel cladding samples consists of three main components or systems. These are the heating system, the pressurization system and the data acquisition system. A detailed description of each system is given below.

2.1 The Heating System

After some preliminary experimentation, it became apparent that the proposed use of cartridge heaters for heating the test specimens could not meet all the heating requirements of the proposed test program. As a result, a tubular-design electrical resistance furnace was chosen. The tube furnace was designed and built in-house. A schematic cross-sectional diagram of the furnaces is presented in Figure 1 and a photograph of the furnace in its vertical and horizontal configurations is shown in Figure 2. The furnace consists of a 45.7 cm (18") or 30.5 cm (12") long by 5.1 cm (2") bore high purity alumina ceramic tube and a 48.3 cm (19") long by 38.1 cm (15") diameter cylindrical stainless steel shell. Heating elements were made by winding a helical coil with an appropriate number of turns using 16 gauge Chromel-A wire. The individual turns of the heating element were spaced suitably and cemented to the alumina tube using high temperature ceramic cement. Fiberfrax (alumina-silica bulk fibre) was used for thermal insulation of the central heating element and alumina tube.

Temperature control of the furnaces was achieved using a Thermo Electric model 940 Digital Process Controller operated in tandem with a Halmar model LZF1-2425 SCR Power Controller. The signal used for closed-loop temperature control was provided by a type-K thermocouple placed at a suitable location on the bore surface of the alumina tube. A schematic diagram of the temperature control logic-circuit is presented in Figure 3 and a photograph of the temperature control panel is shown in Figure 4.

An auxiliary part of the specimen heating system is the cylindrical quench tank, shown partially under the vertically-oriented furnace in Figure 2. In oxidation tests where water quenching is scheduled, the aluminum alloy cylinder is filled with tap water and placed beneath the furnace and specimen-fixture (stainless steel tube) assembly. Immediately upon completion of the prescribed oxidation time, the Fiberfrax Duraboard covering the opening in the bottom of the furnace is pushed aside and the specimen-fixture assembly is plunged into the quench tank. This quenching action allows the experimenter to qualitatively assess the ability of a hot and partially oxidized fuel cladding sample to survive a rather severe thermal shock treatment.

2.2 The Pressurizing System

A schematic diagram of the pressure control circuit is shown in Figure 5. The pressure source is a regulated inert gas (argon) cylinder. This type of pressurization has been used successfully in a test facility developed/3/ for biaxial deformation of Zr-2.5 wt % Nb pressure tube samples at elevated temperatures. As shown schematically in Figure 5, the sample pressure is measured using a Validyne pressure transducer mounted very close to the specimen outside the furnace. Small pressure increases associated with temperature ramping to the desired test temperatures were manually relieved via use of metering/shut-off valves installed immediately downstream of the argon gas cylinder regulator. During the long isothermal phase of the test, the pressure was maintained at a constant value via use of a cylindrical surge or expansion tank.

The pressure circuit also contains a pressure switch. This device was used to monitor accurately the elapsed time to rupture. Once the pressure switch senses the pressure drop associated with specimen failure, it performs the following functions:

1. de-energizes a solenoid valve which serves to isolate the sample from the pressure source;
2. triggers a relay which shuts off the power to the furnace;
3. shuts the power to the elapsed time indicator.

The above elapsed time indicator (one second resolution) was used because it was not practical to use the microprocessor-based data acquisition system to accurately monitor the time to failure.

Pressure sealing of the test samples, which were outer element, Bruce-type Zircaloy-4 fuel cladding, was accomplished using FLODAR fittings. These FLODAR fittings use a self-flaring mechanism for making pressure-tight joints. To use these fittings, the outboard bearing pad had to be cut off from the fuel pencils. Prior to testing, all samples were pressure tested for leaks by immersing the test sample assembly in a aluminum trough filled with water.

2.3 The Data Acquisition System

The data acquisition system consists of a microprocessor-based Acurex Autodata Ten/10 data logger and an elapsed time counter. This data logger is capable of monitoring 20 temperature and

analog voltage channels. In a given test, the temperature at three locations on the test sample and the specimen pressure are monitored and recorded at appropriate time intervals. The data acquisition system is equipped with battery back-up to prevent loss of data due to a power outage.

As mentioned earlier, the time to failure for a given pressure test was monitored using an elapsed time counter which has a time resolution of one second. This counter is started at the beginning of the temperature ramp. Upon specimen failure, the counter's power is turned off and the elapsed time (to failure) is retained in the counter's mechanical display. The use of this device permits accurate times to specimen failure to be obtainable.

3.0 PERFORMANCE CHARACTERISTICS OF THE TEST FACILITY

3.1 The Heating System

Since the heating of the test specimens is by indirect electrical resistance and since the furnaces used have relatively large thermal masses, it was difficult to obtain constant heating rates during the temperature ramping phase of the heating cycle. As shown in Figure 6, the heating rates invariably decrease as the hold test temperatures were approached. The initial heating rate was about 0.6 K/s and the final heating rates were typically in the range 0.15-0.3 K/s, depending on the furnace orientation and the test temperature. During the temperature hold, the specimen temperature within the central 10-13 cm zone was at least within ± 3 K of the predetermined test temperature. Furthermore, during the temperature hold, the temperature ripple at any location within the central monitored zone was only ± 1 K, as shown in Figures 7 and 8.

3.2 The Pressurization System

Figure 9 presents data obtained from a constant pressure rupture test conducted at 973 K. As shown in the pressure plot, the differential pressure of 0.6 MPa was maintained within ± 0.002 MPa until just prior to specimen failure. This type of pressure hold was typical of that achievable using the pressure control circuit shown in Figure 4. The above results indicate that a constant pressure test can be carried out relatively easily using the newly developed test facility.

3.3 Examples of Test Results Obtainable

Figure 10 shows the appearance of fuel cladding samples after they were oxidized in air for periods of one to five days at 923 K and water quenched. The photograph shows that the oxide scales have a characteristic beige to light-brown colour. After four days of oxidation at 923 K followed by water-quenching (specimen 4), the braze HAZ oxide shows signs of severe cracking. After five days (specimen 5), both the parent and the braze HAZ oxides show signs of severe cracking, with the latter also exhibiting spalling. The above observations show clearly that the braze HAZ material oxidizes much more rapidly than the parent material at 923 K in an air environment.

Figure 11 shows the condition of samples after they were biaxially deformed at elevated temperatures. The photograph illustrates that at relatively high test pressures (~1.9 MPa), the samples invariably deform by ballooning of the parent material followed by rupture in the most severely ballooned regions. Depending on the test temperature and pressure, the specimen may rupture during heating to (specimen 1) or shortly after achieving (specimen 2) the desired test temperature. Therefore, at high test pressures, the samples degrade primarily by straining in the

parent material. At intermediate pressures and temperatures, the samples degrade by a combination of oxidation and straining and the final failure occurs by rupture in the ballooned region in parent cladding material (specimen 3). At relatively low internal pressures, the samples degrade principally by loss of wall thickness due to oxidation. In this situation, the failures occur invariably in the central braze HAZ because this region oxidizes much more rapidly than the parent material (specimens 4 and 5). Furthermore, the failure sites were typically at the edges of the bearing and spacer pads.

4.0 SUMMARY

A test facility capable of oxidizing fuel cladding samples at temperatures up to 1273 K and simultaneously biaxially deforming the samples has been developed at Ontario Hydro Research Division. Examples of test results obtainable using the newly developed facility indicate that a large variety of oxidation and biaxial tests may be carried out. The test facility was designed to handle mainly single elements of CANDU reactor fuel cladding. However, the bore of the tube furnaces is such that a small array of fuel pencils may also be tested to investigate the effects of element-element or element-restraint interactions as well.

ACKNOWLEDGMENTS

The authors wish to thank Mr. J. Novak of the Fuel and Physics Department of the Technical and Training Services Division and Mr. J.H.K. Lau of the Nuclear Studies and Safety Department of the Design and Development - Generation Division for useful discussions. Development of the test facility was partially funded by the Technical and Training Services Division.

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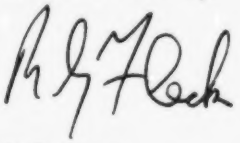

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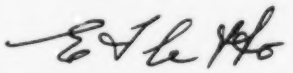

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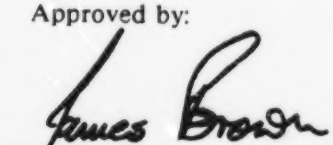

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REFERENCES

1. J.H.K. Lau, Memorandum to C. Blahnik, "Experimental Program to Assess Sheath Failure in the Temperature Range of 500°C - 950°C", File No. 906-N-03500T5, October 17, 1984.

2. E.T.C. Ho, Ontario Hydro Research Division Report No. M84-157-K, November 30, 1984.

3. E.T.C. Ho, and A. Donner, Ontario Hydro Research Division Report No 83-18-K, February 2, 1983.

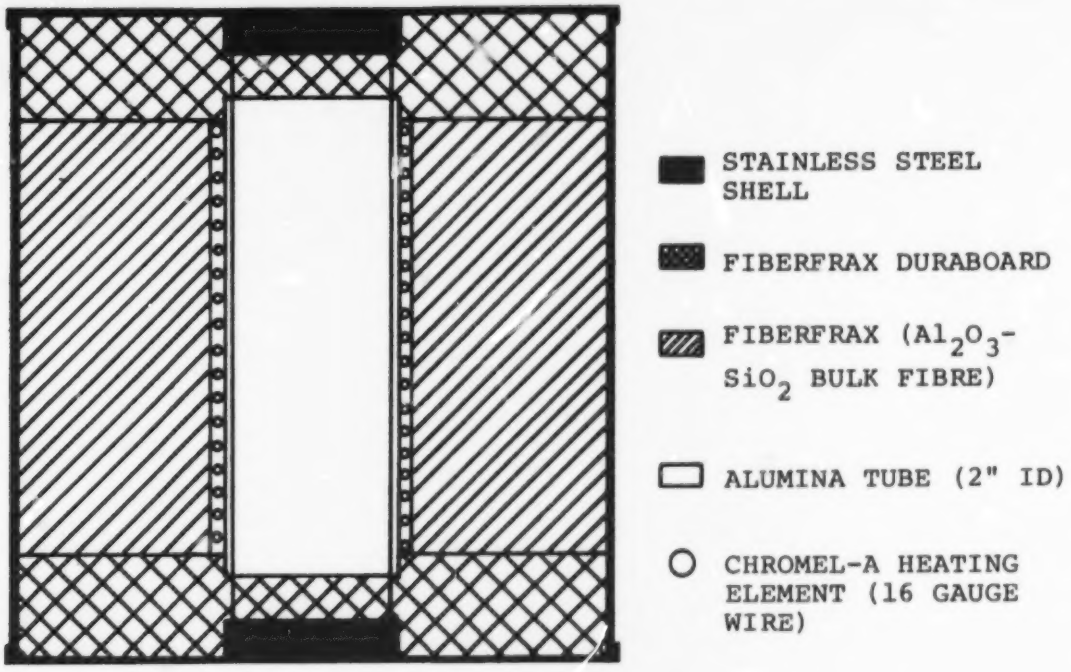

Figure 1: Schematic cross-sectional diagram of the tube furnaces used for heating the test specimens.

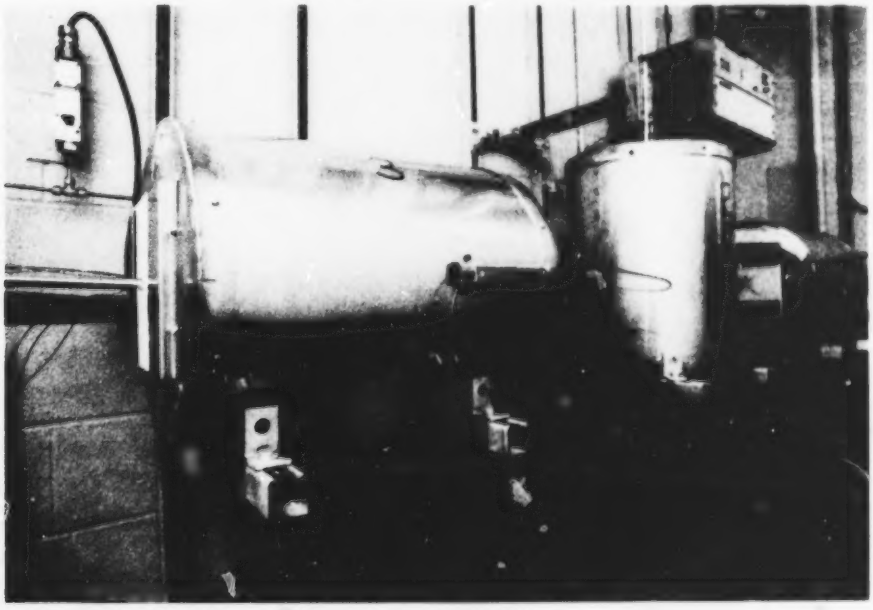

Figure 2: Photograph illustrating the tube furnaces in its two main operating orientations or configurations.

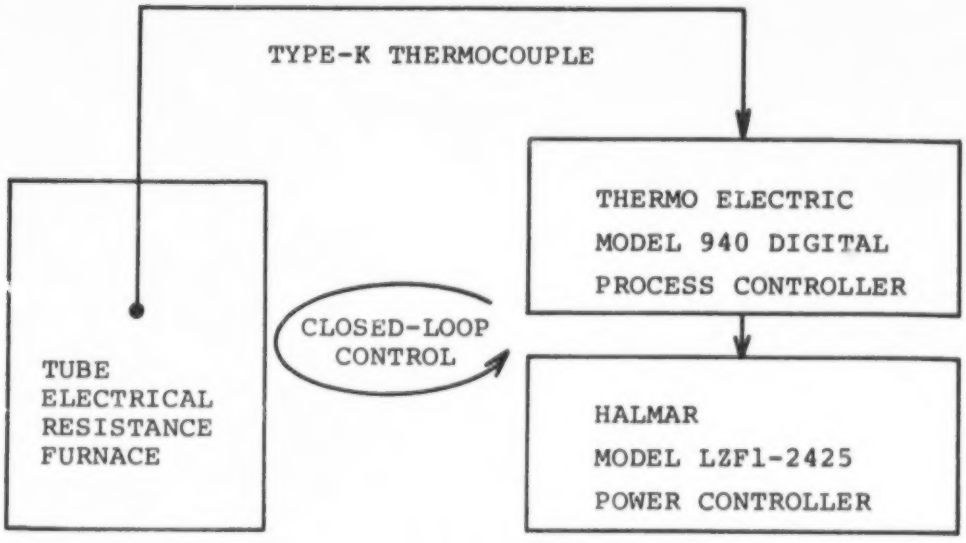

Figure 3: Schematic diagram of the closed-loop control circuit for temperature control.

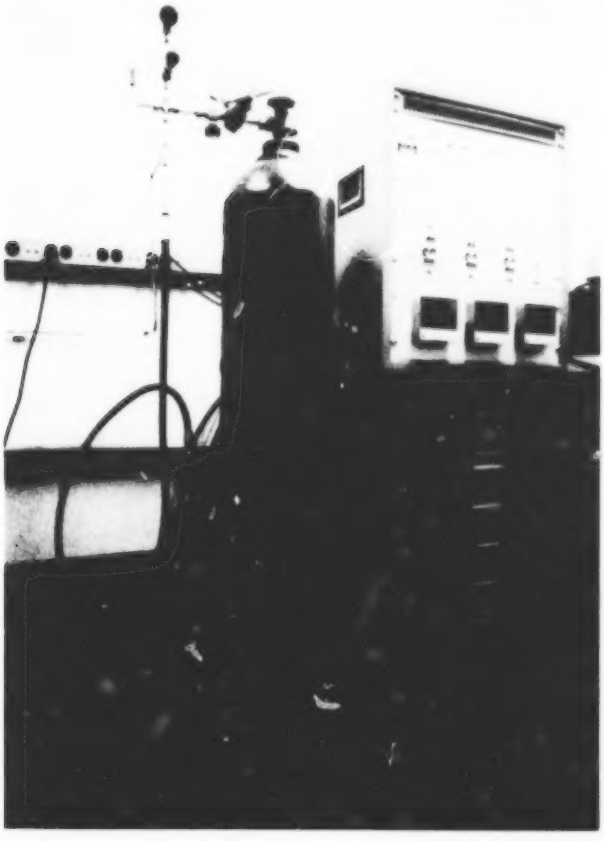

Figure 4: Photograph of the temperature control panel, the pressure source and the stainless steel expansion tank.

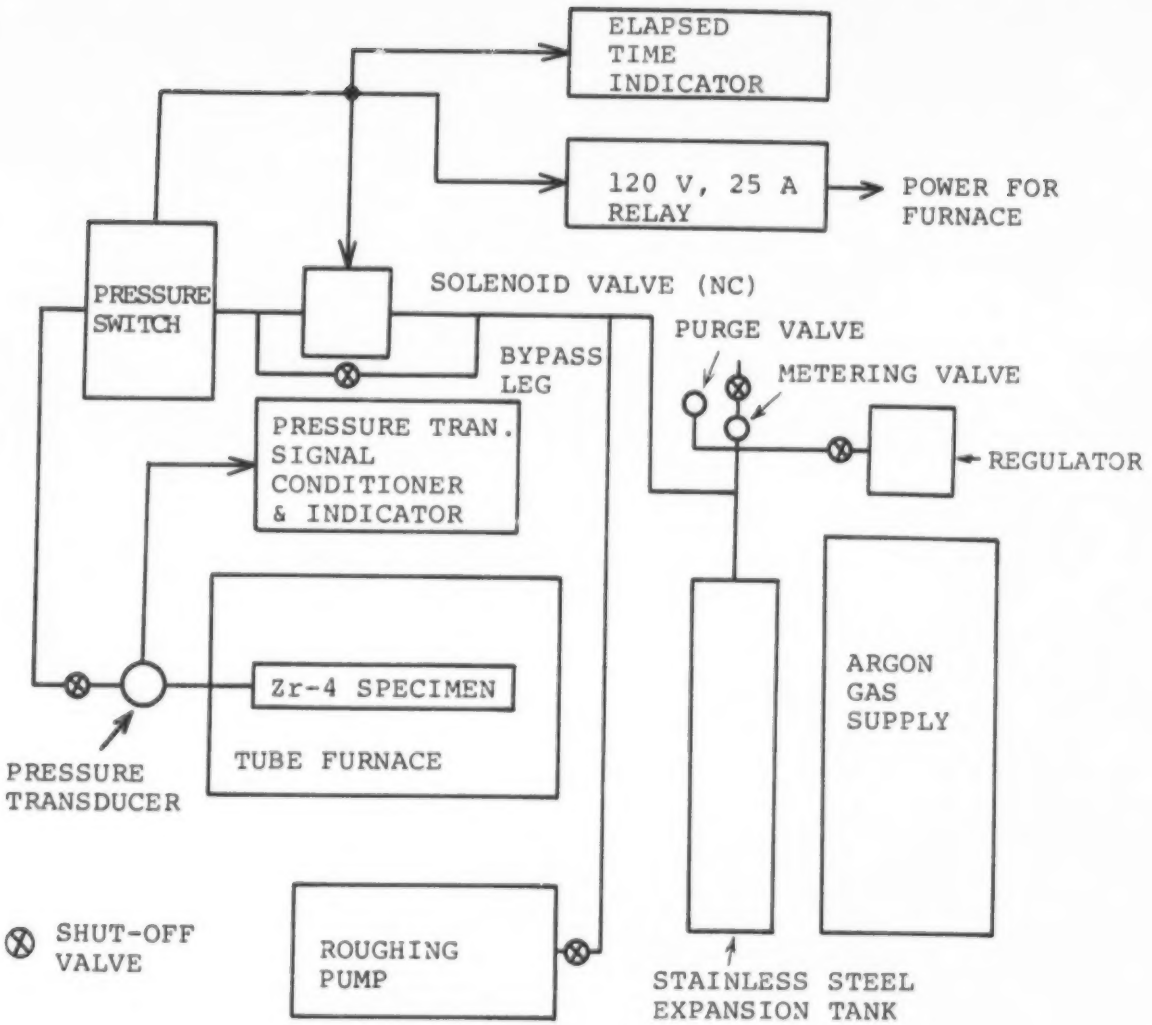

Figure 5: Schematic diagram of the pressure control circuit.

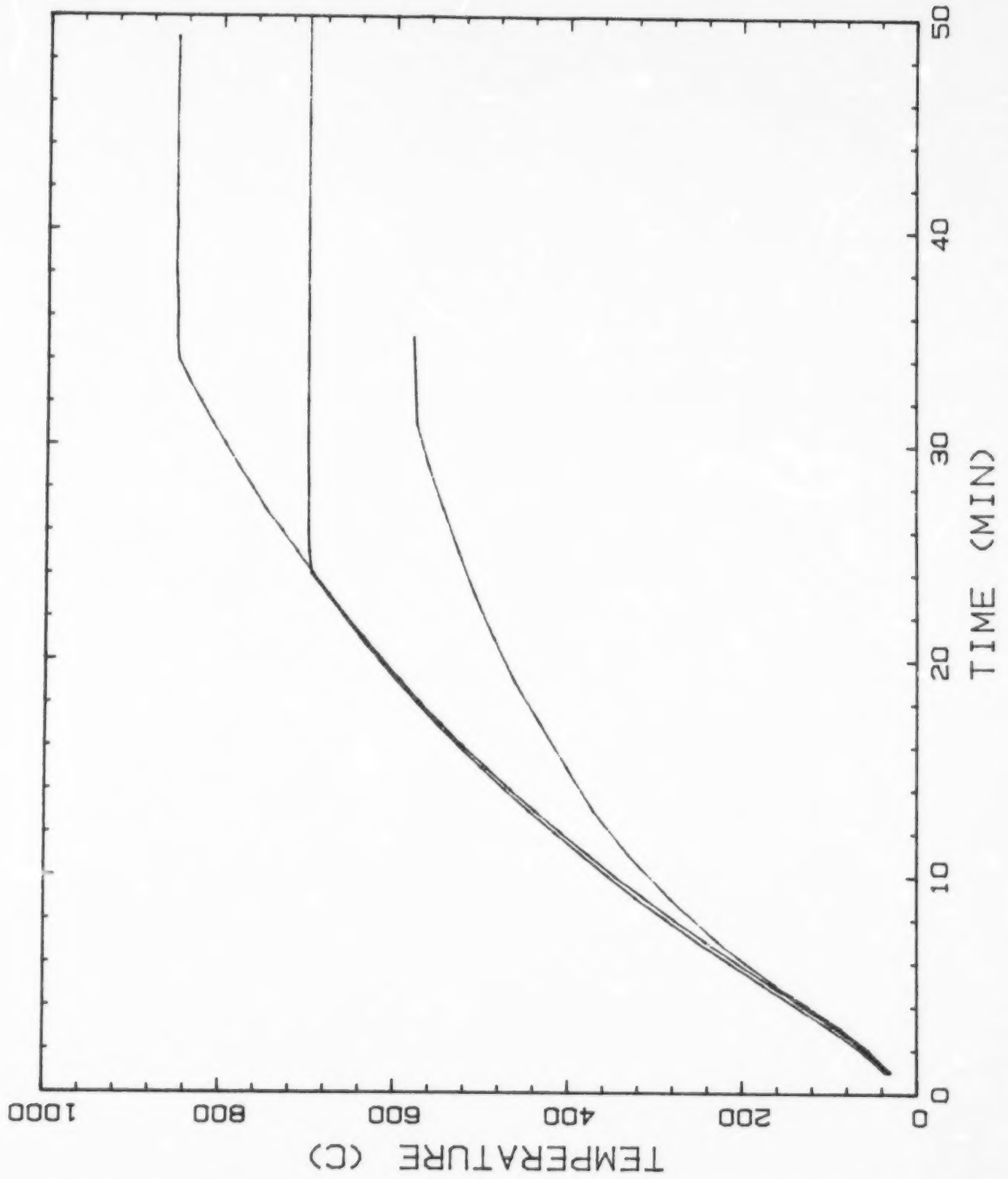

FIGURE 6: PLOTS ILLUSTRATING THE MAGNITUDES OF HEATING RATES OBTAINABLE.

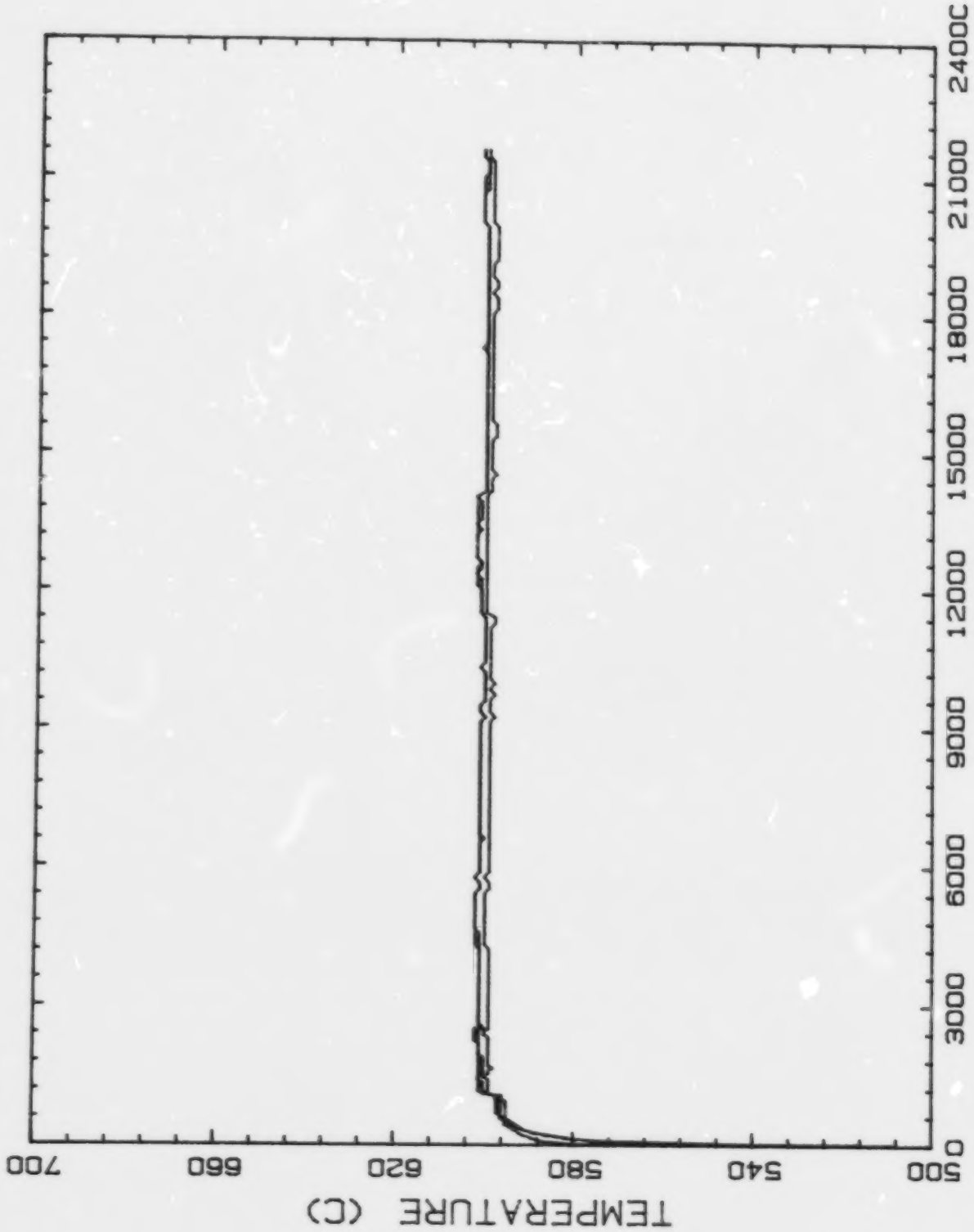

FIGURE 7: PLOTS ILLUSTRATING AXIAL TEMPERATURE GRADIENTS AND TEMPERATURE STABILITY OBTAINABLE IN A VERTICAL SETUP FOR THE TUBE FURNACES.

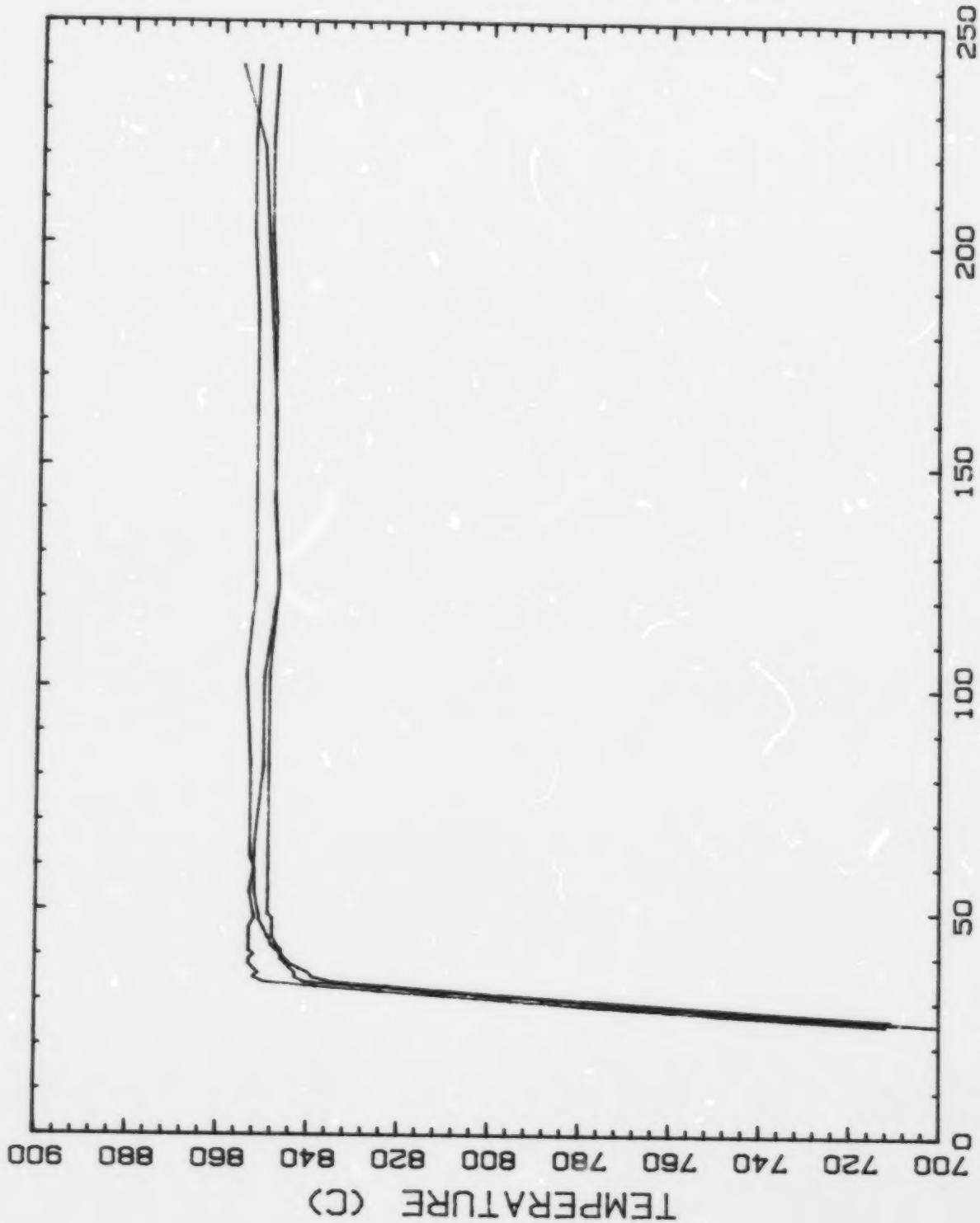

FIGURE 8: PLOTS ILLUSTRATING AXIAL TEMPERATURE GRADIENTS AND TEMPERATURE STABILITY OBTAINABLE IN A HORIZONTAL SETUP FOR THE TUBE FURNACES.

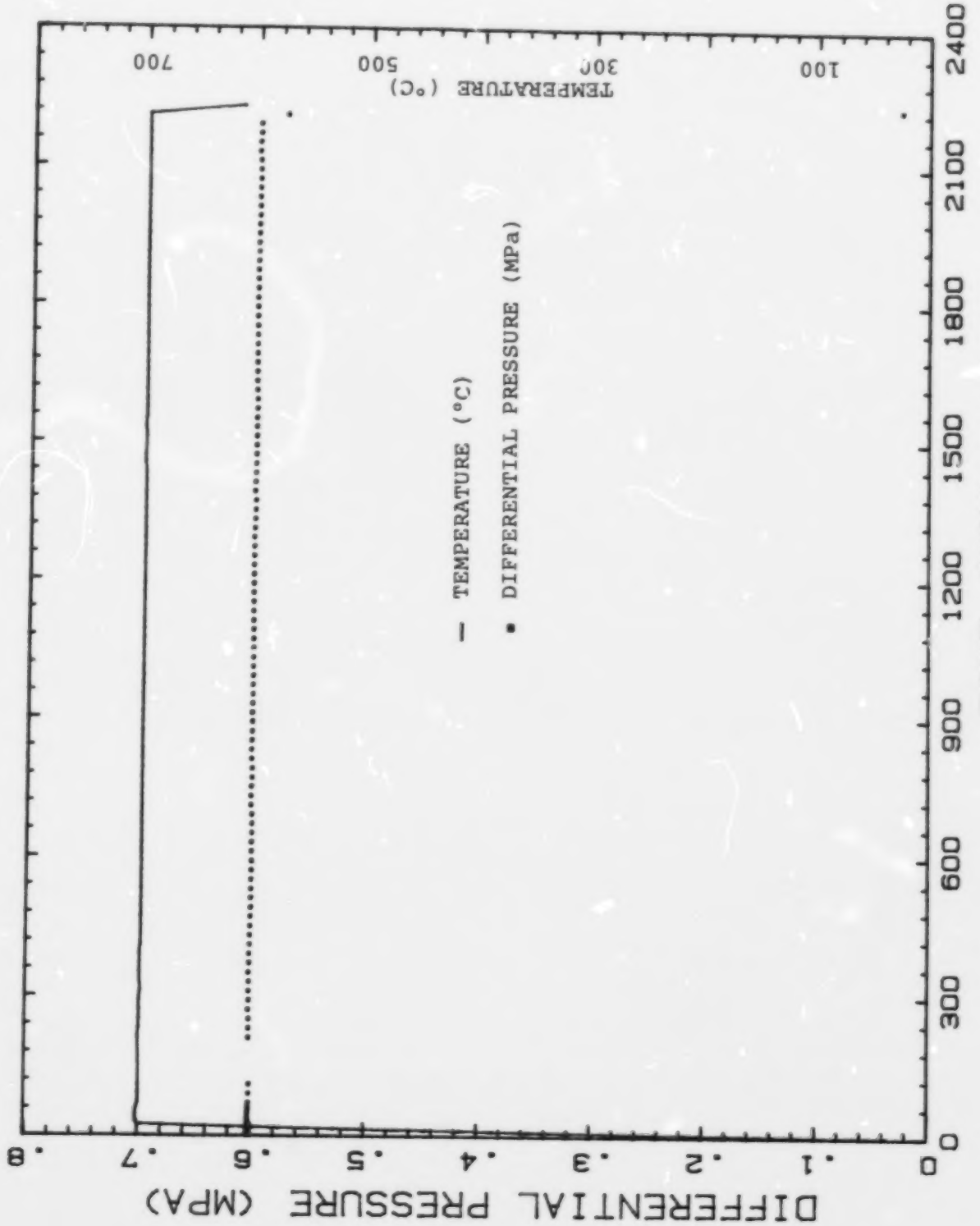

FIGURE 9: PLOTS ILLUSTRATING THE TYPES OF PRESSURE AND TEMPERATURE CONTROL OBTAINABLE IN A TEST TO RUPTURE AT 0.6 MPA AT 973 K.

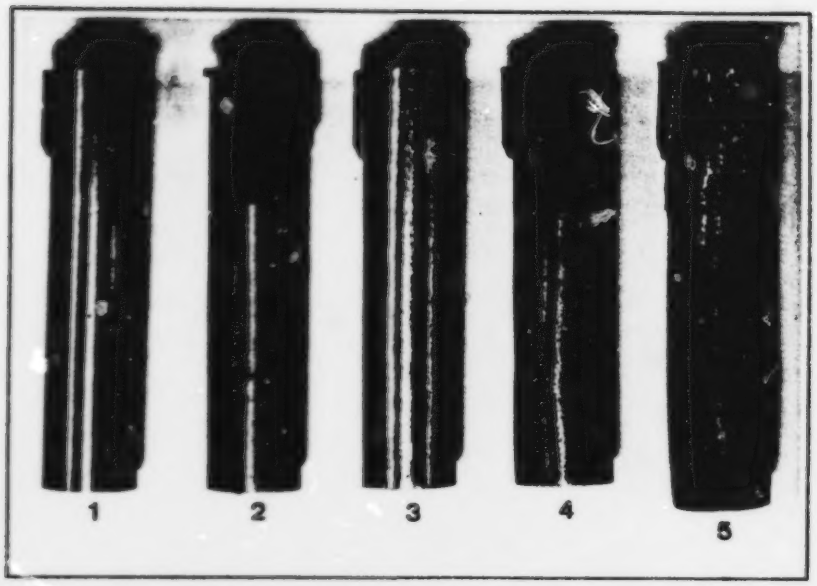

Figure 10: Photograph illustrating the appearance of samples after oxidation for various times at 923 K followed immediately by water quenching.

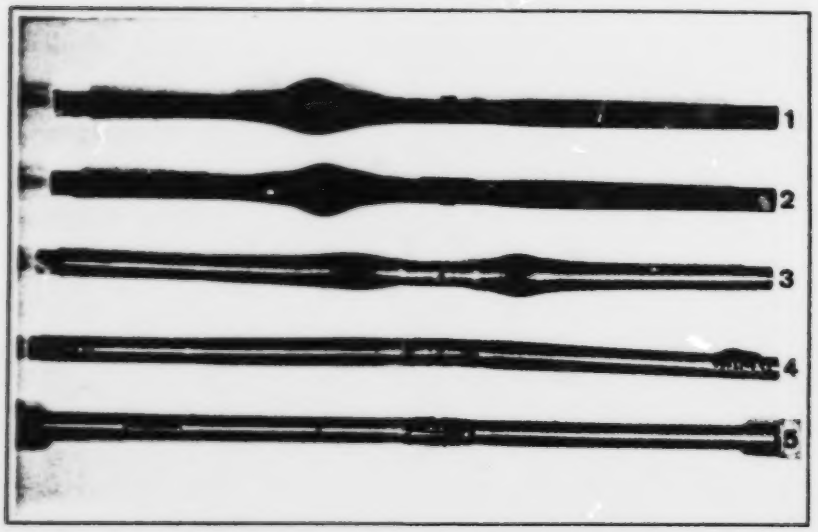

Figure 11: Photograph illustrating the appearance of samples after biaxial deformation at elevated temperatures under various differential internal pressures.

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